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Design of an underwater explosion simulator.

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DESIGN OF AN UNDERWATER EXPLOSION SIMULATOR

by

LT. JOHN A. McMORRIS II, U.S.N.

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF NAVAL ENGINEER

and

FOR THE DEGREE OF MASTER OF SCIENCE

IN NAVAL ARCHITECTURE AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1963

THESIS SUPERVISOR: HAROLD E. EDGERTON, SC.D., D.ENG.

Professor of Electrical Measurements

DESIGN OF AN UNDERWATER EXPLOSION SIMULATOR

by

JOHN A. McMORRIS II, LIEUTENANT, U.S. NAVY

B.S., U.S. Naval Academy

(1957)

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Submitted to the Department of Naval Architecture and Marine
Engineering on May 17, 1963, in partial fulfillment of the
requirements for the Master of Science degree in Naval
Architecture and Marine Engineering and the Professional
degree, Naval Engineer.

ABSTRACT

Desired characteristics of a hydraulic shock test facility
are discussed, and the relative merits of possible driver
configurations are examined. Primary emphasis is given to the
experimental development of a magnetically actuated hydraulic
shock generator, based on the "boomer" developed by Dr. H. E.
Edgerton of M. I. T. The results of systematic variation of
available design parameters are displayed in a series of plots,
and these are used as the basis for a proposed design of an
underwater explosion simulator. Basically, it was found that
any combination of parameters which resulted in an electrical
rise time of less than 50 microseconds resulted in an output
pressure pulse with rise time less than 1 microsecond, for the
driver configurations investigated. Pulse amplitudes obtained
were computed to be approximately 1000 p.s.i., with an electrical
input of 700 joules. Additional test series are recommended
to verify performance of a driver-pressure chamber combination
suitable for use as a test facility.

Thesis Supervisor: Harold E. Edgerton, Sc.D., D.Eng.
Title: Professor of Electrical Measurements

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I. INTRODUCTION

A. Background

Within the last 20 years, considerable advances in the methods and materials of naval architecture have led to the emergence of the deep diving submarine as a promising naval weapons system. In addition to the improved technology required for the design and fabrication of the pressure hull of such a ship, basic design modifications have been demanded for nearly every fitting or device penetrating that hull or mounted external to it. Each such modification must obviously be subjected to thorough testing prior to its acceptance in a final design: One facet of component testing is the verification of hydrostatic performance by subjecting each component to a specified pressure level in a pressure chamber. A second is the examination for possible fatigue problems by imposing a cyclic variation in pressure level over a period of time. A third is the investigation of dynamic response to a pressure pulse, such as might be generated by an underwater explosion.

In fact, this last pressure test is of particular interest to naval engineers. Despite advances in the theory, response to such dynamic loading is difficult to predict analytically, particularly when the pulse is superimposed upon a given hydrostatic loading. To date, precise knowledge has been contingent upon explosive testing at depth. As this procedure is both slow and expensive, attempts have been made to artificially

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produce the pressure history of an underwater explosion within a pressure chamber. It is the purpose of this thesis to examine the design considerations involved in the development of such a test facility, with particular emphasis on the design of an electrically actuated "driver" to produce the desired pulse.

B. Characteristics of an Underwater Explosion

Presumably, the first step in simulating an underwater explosion is to obtain a detailed description of the phenomenon which we desire to simulate. Accordingly, the pertinent characteristics as described by Keil (1)*, are summarized below:

When a high explosive detonates underwater, the almost instantaneous release of energy produces a shock wave which propagates radially outward from the point of detonation. Initially, the velocity of this pressure pulse is about three times the local speed of sound, but its velocity quickly drops to a value just over the local speed of sound. The general profile of such a pulse is as indicated in Figure Ia. It is characterized by an essentially vertical leading edge, and an initial value p_0 which is a function of the amount of energy released (weight of charge) and standoff (distance of observer from explosion). The initial decay is expoential, with time constant τ, and the "hump" shown occurs about one

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* Numbers in parenthesis refer to references tabulated in the bibliography.

FIGURE I

ILLUSTRATION OF PRESSURE WAVEFORMS
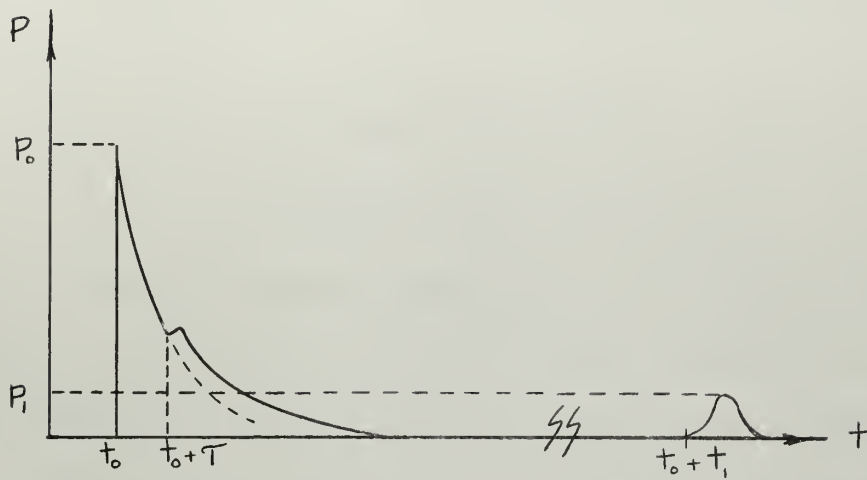
A. PRESSURE HISTORY OF AN UNDERWATER EXPLOSION
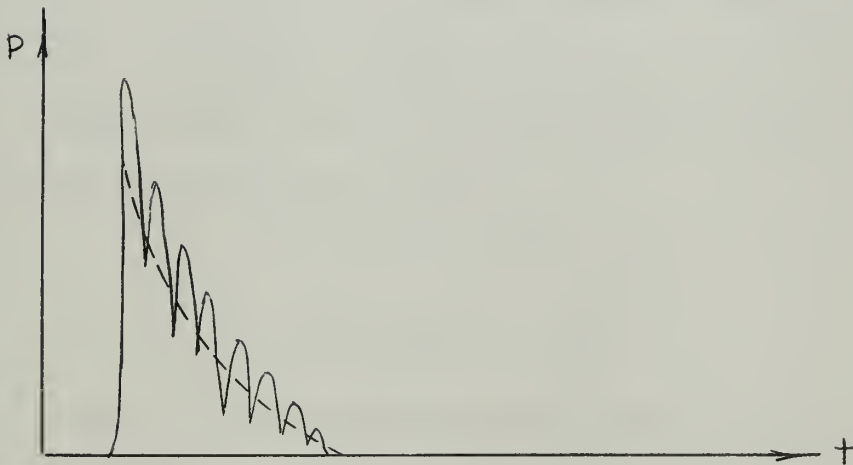
B. PRESSURE HISTORY OF A SIMULATED EXPLOSION

time constant from the leading edge. (It is attributed to energy reflections within the gas bubble generated by the explosion.) Specifically, the following empirical relationships hold:

$$p_o = 21,600(W^{1/3}/R)^{1.13} \quad \text{psi} \qquad (1)$$

$$\mathcal{T} = 58W^{1/3}(W^{1/3}/R)^{-0.22} \quad \mu\text{sec} \qquad (2)$$

where W is the equivalent charge weight in pounds of TNT (one pound of pentolite releases as much energy as 1.3 pounds of TNT; one pound of HBX is equivalent to about 1.5 pounds of TNT, etc.), and R is the standoff in feet.

About half the energy of the explosion remains in the gas bubble, which expands, overshoots its equilibrium size, and collapses. Upon collapsing in a minimum, the bubble emits a second pressure pulse, about 1/10 the magnitude of the first publse, and without the vertical leading edge characteristic of a shock front. Roughly, if T_1 is the interval between the first and second pulses, and p_1 is the peak pressure of the second pulse:

$$T_1 = 4.36W^{1/3}/Z_o^{5/6} \quad \text{sec} \qquad (3)$$

$$p_1 = 2000W^{1/3}/R \quad \text{psi} \qquad (4)$$

where Z_o is equal to the charge depth plus 33 feet.

The gas bubble continues to oscillate for some time after the explosion, but experience indicates that the energy contained in the first two pulses generally accounts for such damage as may be done.

C. Characteristics Desired of Test Facility

From an engineer's viewpoint, for test purposes it is neither necessary nor desirable to produce an exact duplicate of the rather complex pressure signal described above. Perhaps, a minimum standard for a test facility might be the generation of a single pulse of "reasonably short" rise time and an "approximately exponential" decay. Just how "reasonable" and how "approximate" one can be depends, ultimately, on what can be readily achieved, and upon the desired degree of correlation between the outcome of laboratory tests and actual explosive testing.

Ideally, equipment design must be based upon the hypothesis of withstanding the explosion of a given weight of charge at a given standoff, without serious damage. By contrast, current test practice converts such a standard to the more approximate specification that the equipment withstand a given impulse--- that it, that the integral under the pressure-time curve as measured at the equipment be of a particular value without resulting in serious damage--- and laboratory tests are conducted accordingly. Such a specification leaves the particular combination of peak pressure and decay rate used to realize the desired impulse a characteristic of the specified test facility, rather than a characteristic of some hypothetical explosion. Again, justification of such an approximation is based strictly upon the results obtained.

Considering the above, it would seem advisable to base the evaluation of any proposed test device upon a comparison

with an operating test facility. Such a facility is located
at the Portsmouth Naval Shipyard. It consists of a cylin-
drical pressure chamber of 8" internal diameter, about 20"
long, mounted vertically. The upper end of the chamber is
fitted with a piston, upon which a weight is dropped to pro-
duce the desired pressure pulse. The lower end of the
chamber is flanged to receive test specimens. Normally, the
chamber is filled with glycerine for test purposes.

    According to Mr. C.J. Chwalek of the Impedance, Shock,
and Vibration Test Section, Portsmouth Naval Shipyard, the im-
pact of the weight upon the piston produces a steep pressure
pulse with a rise time of about 0.2 ms and a total duration
of about 0.4 ms. However, this pulse is reflected re-
peatedly from the ends of the chamber, so that a test specimen
is struck by a series of overlapping pulses of decreasing
amplitude, with a repetition frequency of about 3 kc. The
disturbance continues for a period of about 3 ms before
dying out. The general appearance of this waveform is
shown in Figure Ib. The suitability of this waveform as a
"synthetic explosion" is based upon the hypothesis that,
providing all natural resonances of the equipment under
test occur well below 3 kc, the item under test does not
respond to the individual pulses but rather to the mean en-
velope of the overall waveform. Obvious problems can arise
if the item under test does have a mechanical resonance near
or above 3 kc.

    It might be noted in passing that the device described

has several pertinent features, aside from the waveform pro-
duced, which affect its suitability as a test instrument:
For example, one can easily control magnitude of the im-
pulse generated by varying the size of the weight or the
height of drop. In addition, once the chamber has been
brought to the desired hydrostatic pressure, it is possible
to conduct repeated tests at various impulse levels on the
same specimen without pausing to bleed down and empty the
chamber between tests. This can result in a significant
saving of time when a large number of tests have been
scheduled. Further, though the test facility is intended to
produce simulated underwater explosions, water is not used
as a test medium. Obviously, other liquids may offer
advantages as regards the generation and propagation of
hydraulic shock. Finally, by restricting the cross
sectional area of the test chamber, it is possible to pro-
duce relatively intense pressure pulses with relatively
low energy input: thus, it is possible to simulate the
pressure history of a given explosion with much less total
energy than is released by an explosive charge. An obvious
limit to the economics offered by a small chamber, however,
is the contemplated size of specimens to be tested.

D. Objectives in Development of Electrical Drive

The basic motives for developing an electrically driven
test facility are many and varied. First, it is anticipated
that most or all of the operational advantages of the current

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mechanical facility--- e.g., ease of adjustment, etc--- could
be retained, and second, there is the distinct possibility of
better control over the waveform generated. Specific items
of interest are faster rise time, better control of the
shape of the envelope, provision for generating the second
pulse described in the section on underwater explosion
characteristics, and, possibly, greater range of variation
of the size of the impulse generated.

II. PROCEDURE

A. Preliminary Selection of Driver Design

Although the energy level utilized to create an arti-
ficial explosion within a pressure chamber may be small
compared to the energy released by detonation of a large
explosive charge, it is not small by normal standards. The
driver contemplated for this facility must be capable of
receiving a pulsed electrical input of 10,000 joules or
more, and coupling this energy with minimum attainable
rise time into the test medium. Presumably, if an electrical
driver is used, a rapid discharge capacitor bank would be
the optimum means of storing the energy, pending its rapid
release into the chamber. Selection of a device to con-
vert this electrical energy into pressure pulse energy is
not so obvious, however. There are relatively few devices
which are capable of operation at the indicated energy
levels, while still offering some promise of being adaptable
to an output rise time in the microsecond range. During pre-
liminary study of this problem, three devices were considered:

1. Exploding wires: Since the mid-1700's, it has
been recognized that if a large capacitor bank is discharged
through a short length of fine wire, the wire will explode,
emitting a brilliant flash of light and a cylindrical shock
wave. Chace (2) advances the theory that resistive heating
quickly raises the wire far above its boiling point, but
that the absence of a container, (i.e., the lack of a micro-

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scopically dirty surface at which vaporization can be
initiated) causes the liquid-vapor transition to be de-
layed for beyond equilibrium. He hypothesizes that when
finally "triggered", the transition occurs with explosive
violence. Conceivably, such a technique could be used to
generate the desired test pulse.

Unfortunately, the use of exploding wires seems to
involve three significant disadvantages for the application
considered: First, energy release occurs within a very small
volume, a situation which is not conducive to the development
of planar pressure fronts within the short length of a
pressure chamber. Second, use of this technique might pre-
sent problems were it considered desirable to use a flam-
mable liquid as the test medium. Finally, and perhaps, most
seriously, it would be necessary to replace the wire before
a second pulse could be generated. As mentioned above, any
requirement that the chamber be opened between "shots" would
comprise a serious operational drawback.

2. Electric arc: Given sufficiently high voltages, one
could dispense with the wire described above by striking an arc
between two electrodes immersed in the test liquid. Normal
electrode life should permit several tests before it became
necessary to reopen the chamber. (In fact, electrode life
might be prolonged by the fact that the electrodes would
be liquid cooled.) However, this technique would still
suffer from the other disadvantages described above, and
might present an even greater safety hazard if used in con-

junction with flammable liquids.

3. Sonar transducer: Finally, it might be possible
to "speed up" a conventional sonar transducer in which the
interaction between electric or magnetic fields and a material
body are used to drive that body forcibly into a liquid medium,
thereby creating a pressure signal. One advantage of such
a device is that the diameter of the driven element can
be nearly as large as the internal diameter of the chamber,
thus simplifying the development of a planar wave front.
Further, Dr. H.E. Edgerton of M.I.T. has recently pioneered
the development of a high-speed transducer (known as a "boomer")
which produces steep, high intensity pressure pulses for use
in oceanographic research (3,4). The pulse characteristics of
production model boomers are not dissimilar to those of the
driven pulse of the Navy's mechanical test facility: i.e.,
rise time of about 0.2 ms, and duration of 0.4 to 0.5 ms.

The major components of Dr. Edgerton's boomer are a
flat, spirally wound coil of ribbon wire (rectangular cross
section), and a flat, circular aluminum plate of slightly
greater diameter than the coil. The coil is encapsulated
in an epoxy pancake, and the plate is clamped to the coil
with steel (or rubber) springs. When a capacitor bank is
discharged through a triggered spark gap into the coil, the
rapid buildup of an intense magnetic field gives rise to
strong eddy currents in the plate. Interaction of these eddy

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currents with the field gives rise to a force which tends to violently separate the plate and the coil. The springs limit the motion of the plate to about 3/4", then return it to rest against the coil.

Early models of the boomer were designed to operate in conjunction with a 500 to 1000 joule capacitor bank, and had an efficiency of conversion of electrical to pressure pulse energy of about 12%. The demand for more powerful pulses has led to the development of models which utilize a 13,000 joule bank. To avoid coil damage in the more powerful models, two coils are counted in series, back-to-back, and a plate is mounted to the outer face of each coil. In this array, the front plate serves as the driver, while the rear plate serves primarily to develope a balance of forces, so that the coils will not be hurled backwards as violently as the plate is hurled forwards.

Inasmuch as the boomer has none of the disadvantages discussed for exploding wire or electric arc drivers, and offers promise of being adaptable to even shorter rise time than that cited above, it was tentatively selected as the driver for the contemplated test facility.

B. Investigation of Test Media

When a given quantity of energy is released at a given rate in a liquid medium, the rise time, peak magnitude, and duration of the resultant pressure pulse are a function of the physical parameters of that liquid. Theoretically, it

should be possible to compute the relationship between
these parameters and the desired pulse characteristics,
and thus determine the optimum liquid to use with a given
driver. Unfortunately (as pointed out by Dr. Donald Ross
of the firm of Bolt, Beranek, and Newman), such calculation
must be based on the high pressure equation of state of
the liquid under consideration: a relationship which, in
general, is unknown. Dr. A.H. Keil (currently Technical
Director, David Taylor Model Basin) verified the lack of
theoretical groundwork as regards high pressure behavior
of real liquids, and further stated that very little
experimental data was available for liquids other than
water. It would appear that there has been relatively
little motivation for research in this particular field.

All the above notwithstanding, it is still apparent
that not all liquids are equally suitable as test media.
Aside from the question of compatability with materials
under test (e.g., neoprene seals, etc.), the most basic
problem governing choice of a particular liquid is probably
the relative ease of forming a pressure pulse which rises
faster than the electrical input to the system. Certainly,
such behavior is a necessity if true shock fronts are to be
achieved. Further, at least qualitatively, two variables
are known to affect this facet of liquid response to a
given energy input: compressibility, and variation of
acoustic velocity with pressure.

Specifically, Cdr. J.R. Baylis has stated that low com-

pressibility was the primary reason that glycerine was selected as the test medium of the Portsmouth facility. He indicated that initial tests were conducted in water, but that glycerine was tried on an experimental basis and proved to yield higher peak pressures and shorter rise time for the same input. He also mentioned that the above improvements in pulse characteristics vanish if even small quantities of water contaminate the glycerine.

Variation of acoustic velocity with pressure--- specifically, an increase in acoustic velocity with increasing pressure--- is a characteristic which results in pulse steepening as a pressure disturbance propagates through a liquid. Keil (1) provides an empirical relationship valid for water at pressures up to 10,000 psi:

$$C = c(1 + 6 \times 10^{-6}p) \quad \text{ft/sec}$$

where c is the local velocity of sound at one atmosphere. Swanson (5) plots data for several organic liquids in the range 1-300 atmospheres. Swanson's data exhibit two interesting characteristics: first, all liquids tested exhibit a linear relationship between acoustic velocity and pressure within the range examined, and second, the slope of this relationship is very nearly identical for all liquids tested except ethyl ether and pentane. The latter two exhibit a slope approximately twice that of the others. Swanson further plotted the relationship

$$C = \sqrt{1/\rho\beta}$$

for four liquids for which ρ and β were known as functions
of pressure over the range investigated. In each case,
the above relationship proved to be non-linear, and although
it did result in an increasing trend for C as a function
of p, it did not correlate well with experimental obser-
vations.

Considering the uncertainties indicated by the above
discussion, and the limitations on available time and
facilities, a simple three point check was conducted using
available hardware to verify boomer performance driving into
different liquids: Specifically, tests were conducted in
water, as a reference standard, glycerine, and pentane. The
driver used was a small, two-plate model (of the type dis-
cussed in the preceding section) illustrated in Figure II.
A commercially available boomer power supply was used as
the energy source, adjusted for 500 watt-second electrical
input to the driver. Inasmuch as no improvement in per-
formance resulted from the use of glycerine or pentane
(see section on RESULTS for details), it was decided that
all further tests would be conducted in water.

C. Investigation of Driver Characteristics

Analysis of the boomer is complicated by the fact that
the instrument is clearly a field-driven device, yet the
geometries involved are sufficiently complex to preclude
mathematical analysis on the basis of field theory. Further,
the dynamics of the problem are of sufficient import to pre-

FIGURE II

5 1/4 " BOOMER

DRIVEN PLATE

BACK PLATE

RETAINING SPRINGS

COIL
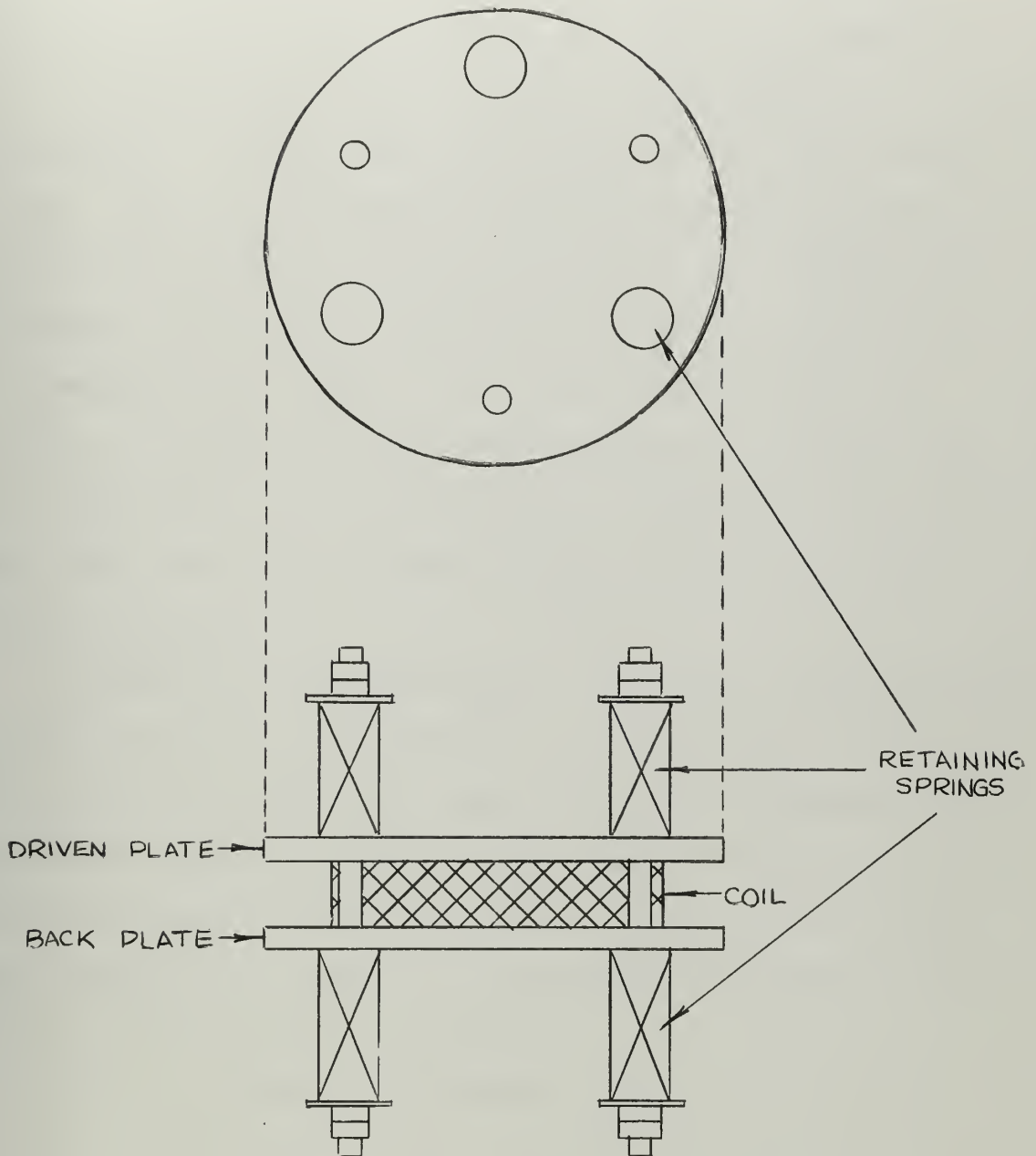
clude the use of such static computational aids as a
teledeltos analogue: the motion of the driven plate is
sufficient to cause significant variation of the degree
of coupling as a function of time. In short, the best
analogue which has been found to cope with the behavior
of the boomer is the device itself. Accordingly, an
experimental program was undertaken with two basic objec-
tives: First, to determine whether the boomer could be
modified to produce true shock fronts--- or, failing that,
determine the minimum attainable rise time--- and second,
by systematic variation of the basic parameters of the
device, to obtain a quantitative measure of the effect of
such variation on the pressure pulse produced. It is hoped
that such data can at least establish trends of use to
future designers.

Recognizing the limitations of available facilities, no
attempt was made to experiment at energy levels typical of a
full-scale test facility. Most tests were conducted with a
standard electrical input of 500 joules. The maximum input
level for any test was 2100 joules. Within these limits,
experiments were conducted to determine the effect of vari-
ation of the following parameters:

> mass of the driven plate
> conductance of the driven plate
> inductance of the driving coil
> capacitance of the energy bank
> operating voltage

To begin with the first item listed above: however complex its behavior, the boomer exhibits the terminal characteristics of an underdamped RLC circuit. At the risk of oversimplification, it can be stated that to reduce the rise time of the pressure pulse, one need only reduce the electrical rise time of the driver circuit, and to reduce the rise time of the driver circuit, one need only reduce the total inductance and capacitance as seen at the terminals. As mass is the mechanical analogue of capacitance, it follows that some reduction of rise time might be realizeable by reduction of the mass of the driven plate.

Since production model boomers utilize an aluminum alloy plate roughly 20 inches in diameter, considerable reduction in mass would seem inevitable, all else remaining equal, should one accept the concept of a driver which must fit within an 8 inch pressure chamber. It was presumed that additional mass reduction could be effected by reducing plate thickness to the minimum capable of withstanding the stresses developed without permanent deformation*. To determine whether or not such additional reduction would significantly improve the output pulse, and how much reduction might be possible, a number of aluminum plates were prepared for testing.

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* For oceanographic work, allowance for erosion by cavitation has resulted in a driven plate somewhat thicker than might otherwise be required. As these plates are readily machined, it is assumed that a shorter life cycle would be acceptable for a test facility, and thus erosion would be no problem.

All were approximately 8 inches in diameter and most were
of the higher strength aluminum alloys with a conductivity
in the range of 35% to 40% that of copper. Thicknesses
ranged from 1/4 inch down to 1/16 inch.

In the absence of any plate, one would presume the field
generated by a boomer coil would be toroidal in nature. The
presence of a conducting plane (such as the plates described
above) adjacent to the coil distorts this field, excluding it
from a particular region of space. In a sense, the force
acting upon the driven plate can be attributed to this con-
tainment or "bottling up" of the magnetic field. Two factors
act to reduce the degree of such containment: the plate is
driven away from the coil, and (since the plate is not a per-
fect conductor), the field begins to penetrate the plate. Pre-
sumably, any change which would tend to nullify these factors
would increase the impulse acting on the plate.

Unfortunately, as the first factor cited is also the mech-
anism by which energy is transferred to the liquid, little
could be profitably done to reduce it*. On the other hand,
use of a more highly conductive plate would obviously reduce
the rate at which the field penetrated the plate--- though at
the cost of added mass, considering such factors as yield

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* A possible exception to this statement would be the use of
  a less compressible liquid, provided that: 1) the driver and
  the liquid completely filled a constant-volume system, and
  2) provision were made to exclude the liquid from the region
  between the plate and the coil.

strength and density of available metals. The effectiveness
of such a change would presumably depend upon the increase
in conductivity attainable and the relative importance of
the two factors cited.

To investigate the above considerations a second family
of plates was prepared. These plates were all approximately
8 inches in diameter by 1/16 inch thick, but varied in com-
position from aluminum alloy, through various copper-aluminum
laminates to pure copper. (The laminated plates were prepared
by bonding various thicknesses of copper and aluminum with
Emerson and Cuming ECCOSEAL W19 low viscosity epoxy.) Nat-
urally, laminated plates were tested with the copper side
adjacent to the coil.

Coil inductance was one parameter which gave more direct
access to electrical rise time. The decision was made to
return to a single layer coil, as contrasted with the back-
to-back series array, to reduce total inductance. The rear
plate was eliminated, and replaced with a rigid, insulating
backing material which firmly supported the coil to prevent
recoil.

Conceptually, at least, the upper limit of coil inductance
is set by the desire to achieve the shortest feasible electrical
rise time, and the lower limit is set by the higher peak cur-
rents which result from reduced impedance: eventually, more
energy would be consumed by resistance of the leads than
would be transferred to the plate. Practically, however,
physical size--- which bears a direct relationship to induct-

ance--- is the determining factor. If the array is to fit
within an 8 inch pressure chamber, the maximum feasible
coil diameter is something under that dimension. Further,
if the coil is to drive an 8 inch plate, the localized
stresses resulting from the use of any coil appreciably
smaller than that dimension create a serious structural
problem.

For experimental purposes, a series of three coils was
prepared to investigate the effects of varying inductance
within the limits discussed above. Pertinent parameters are
summarized in Table I below:

TABLE I

CHARACTERISTICS OF COILS USED IN TEST SERIES

Coil No.	Ri	Ro	N	L	Q
1	2"	5 1/2"	25	49.8μh	11.7
2	2"	6 1/4"	31	80.1μh	14.0
3	2"	7 7/8"	43	172.0μh	21.5

All coils described above were wound of 0.050" by 0.500"
rectangular, cloth wrapped copper wire. Coils were impregnated
with ECCOSEAL W19 epoxy for insulation and structural strength.
In addition, a 1/16" bakelite sheet was bonded to that face
of the coil which contacted the metal plate for additional
insulation.

The final item of the electrical circuit available for
manipulation was the energy storage bank. Commercial boomers
are controlled by a power supply which provides a 160 μf storage

bank for operation at an energy level of approximately 1000
watt seconds. Provision is made for disconnecting and
shorting half these capacitors for operation at 500 watt
seconds, or for connecting additional storage banks of 2000
watt-second increments for operation at higher energy levels.

To produce pulses with a shorter rise time, the decision
was made to reduce capacitance while increasing voltage, thus
remaining at a constant energy level. As a practical matter,
the range of such testing was limited by available facilities:
The firm of Edgerton, Germeshausen and Grier loaned three
Sangamo Electric energy discharge capacitors, each rated at
14 μf, 20 KV. A power supply was constructed for use in
conjunction with these capacitors which produced a half-wave
rectified output adjustable between 0 and 13 KV*. These
factors established the limits of the test range.

D. Instrumentation

As the boomer is a high energy, magnetically driven
device, suitable instrumentation of the test series presented
some problems: Peak currents through the driver were found
to exceed 20,000 amperes. Coupled with a rise time well
under a millisecond, considerable experimentation was required
to avoid inductive coupling with stray fields. Careful
attention to lead dress, shielding and positioning of com-
ponents was found to be mandatory. In addition, instruments

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* Circuit diagram provided in Appendix B.

with a relatively high level output were found to have obvious
advantages over instruments with low level output.

Transients were displayed on a Tektronix Model 545 oscillo-
scope with Type 53/54K fast-rise (.006μs) preamp, and recorded
by scope photography. In general, it was necessary to use
a 10 - to - 1 attenuator in series with the scope input.

Current through the boomer coil was measured by placing
a 0.00275 ohm resistor between the coil and ground, and ob-
serving voltages developed across the resistor. This resistor
was designed and constructed by Floyd M. Minks (see Figure
IIIa). The major advantage of the design was that test
leads were introduced to the resistor in such fashion as to
be completely shielded from fields induced by current flow
through the resistor: thus, voltages observed must be attrib-
uted solely to the IR drop across the resistor.

Initially, pressure measurements were made with a
Chesapeake Instrument Model SB-154D "eight-ball" hydrophone.
As the minimum rise time of this device was found to be about
40μs, a series of replacement hydrophones were manufactured
and tested, culminating in the design shown in Figure IIIb.
This device, which utilized a 0.400" by 0.060" PZT-5 wafer as
a pickup, was found to have a minimum rise time of about 1μs.
In all tests, hydrophones were positioned 5" from the rest
position of the driven plate, centered with respect to the
plate.

E. Summary of test series

The below list summarizes the various test series which

FIGURE III

DESIGN OF TEST INSTRUMENTS
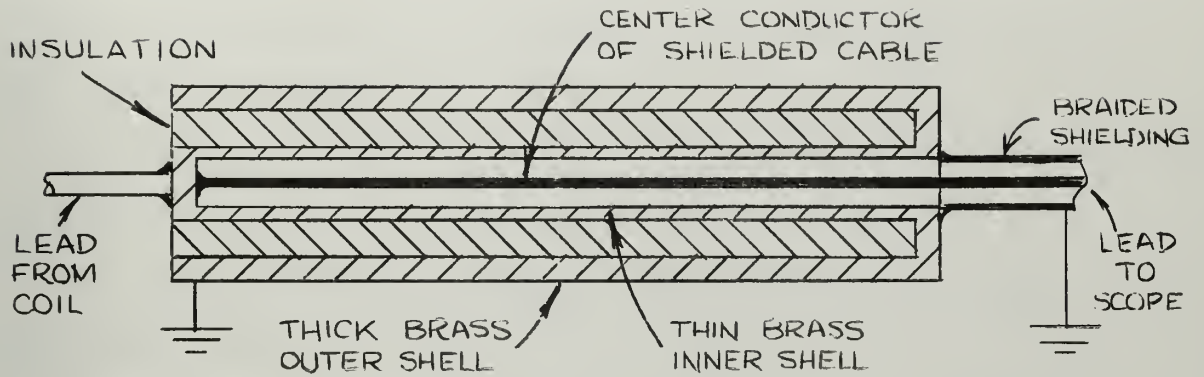
A. GENERAL DESIGN OF MINKS RESISTOR
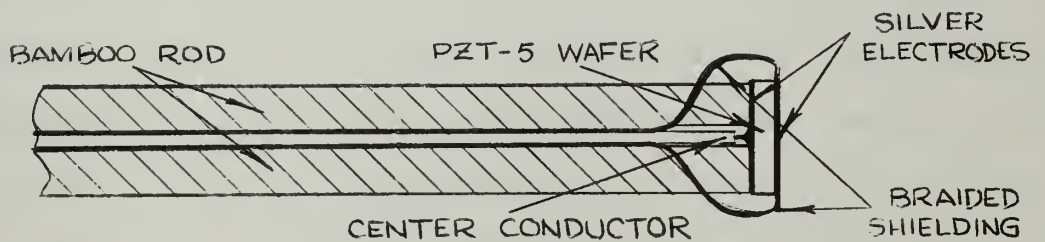
B. DESIGN OF PZT-5 WAFER PRESSURE PROBE

were conducted during this investigation:

1. Test of existing hardware in water, glycerine, pentane, and air.

2. Test of each of 3 coils described above with 1/4", 1/8" and 1/16" Al plates, 500 watt-second input, with supply voltage corresponding to an energy bank capacitance of $80\mu f$, $42\mu f$, $28\mu f$, and $14\mu f$.

3. Test of $49.8\mu h$ coil with $14\mu f$ energy bank, 1/4" Al plate at 2, 4, 6, 8, 10, and 11.4 KV.

4. Test of laminated plates with $49.8\mu h$ coil, $14\mu f$ bank, at 10 KV.

5. Test of 1/4" Al and 1/16" Cu plates at 10 KV with, $49.8\mu h$ coil, $14\mu f$, $28\mu f$ and $42\mu f$ bank.

6. Spot comparison of driver performance in large open tank and 10" cylinder.

Although most tests were conducted in a large, open tank, series 1 and 6 were run in a thin-walled, 10" diameter metal cylinder. Again, availability of facilities was largely the determing factor: while it was recognized that the pressure field produced by the unbaffled driver in an open tank differed vastly from that which would be produced in the hypothesized cylindrical test facility, it was felt that data obtained from open tank tests would suffice to establish a relative basis for comparision of the various driver configurations tested.

The 10" cylinder described above was used as a means to determine device performance under a better approximation of

contemplated operating conditions. As it was feared that this cylinder would not have sufficient structural strength to withstand the complete test series contemplated, its use was restricted to the tests cited.

In series 2 through 6, the driving coil was supported on a wooden platform, as shown in Figure IV, with the driven plate rested atop the coil in the horizontal plane. In the interests of minimizing rise time, no springs or other mechanical constraints were used: the plate was allowed to return to the coil under the action of gravity. As mentioned above, hydrophones were positioned 5" above the rest position of the plate, on the centerline of the array.

FIGURE IV

DRIVER ARRANGEMENT FOR TEST SERIES
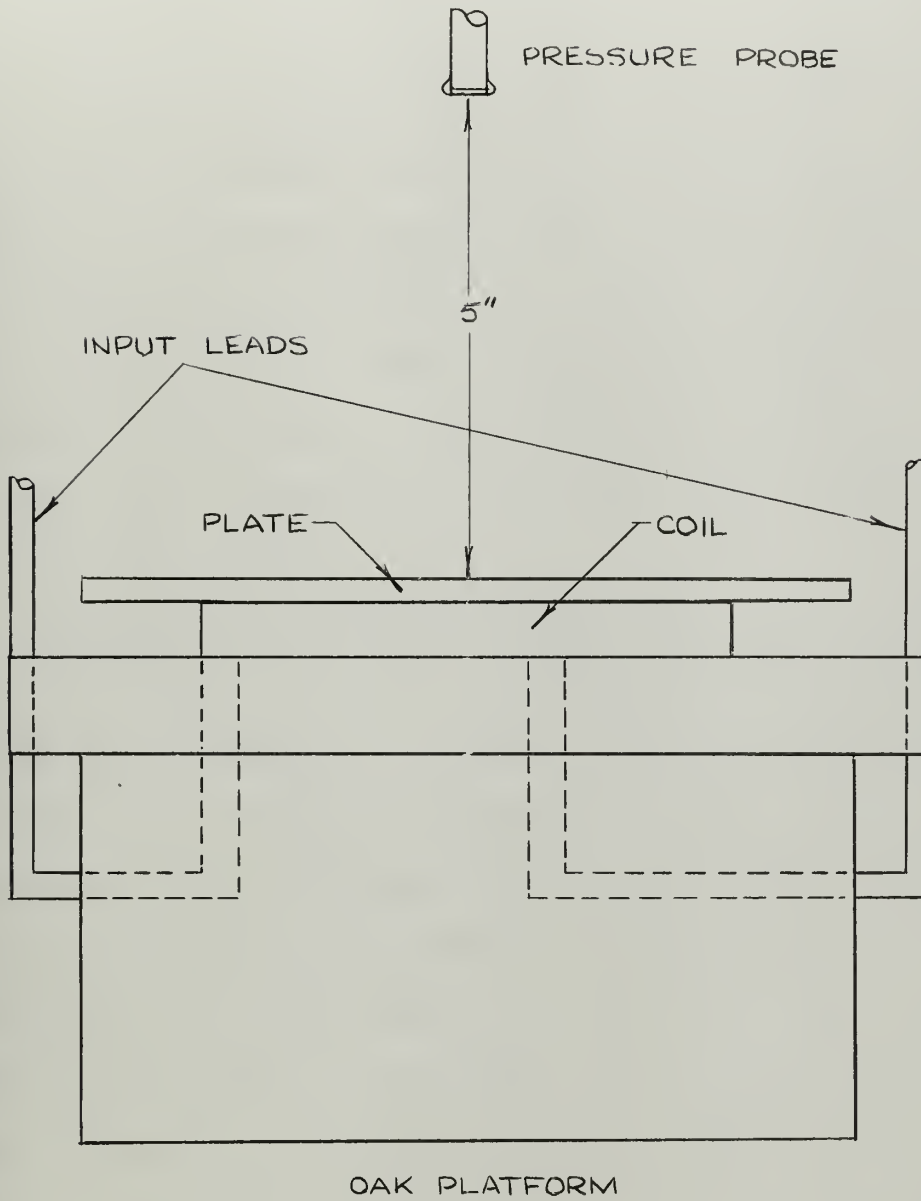
III. RESULTS

A. Electrical performance

1. Comparison of liquids: Changing the characteristics
of the liquid used as the test medium had no discernible
effect upon the electrical signature of the boomer. Tests
were conducted in water, glycerine, pentane, and air, using
the driver illustrated in Figure II in conjunction with an
$80\mu f$, 500 watt second energy bank. In each case the electrical
circuit exhibited a rise time of $61\mu s$, reaching a peak cur-
rent of about 7640 amperes. Once excited, the circuit
exhibited a ring frequency of about 3KC, with a decay time
constant of about $200\mu s$.

2. Variation of L, C, and plate thickness at constant
energy: The effect of varying bank capacitance and plate
thickness while holding energy input constant (at 500 joules)
is plotted, for each coil, in Figures V and VI. Figure V
shows variation of electrical rise time and peak current with
the above parameters, while Figure VI shows variation of ring
frequency and decay time constant. The latter two plots are,
of course, approximate: the change in coupling between the
coil and the plate cause these factors to vary with time.
Thus, the "ring frequency" plotted represents an average
over a number of cycles, while "decay time constant" is, in
fact, the time required for the envelope of the waveform to
decay from I_{max} to 1/e times that value.

FIGURE V

INFLUENCE OF L, C, AND PLATE THICKNESS ON
RISE TIME AND PEAK CURRENT

500 JOULE INPUT

+ 1/4" Al Plate   x   1/8" Al Plate   o   1/16" Al Plate

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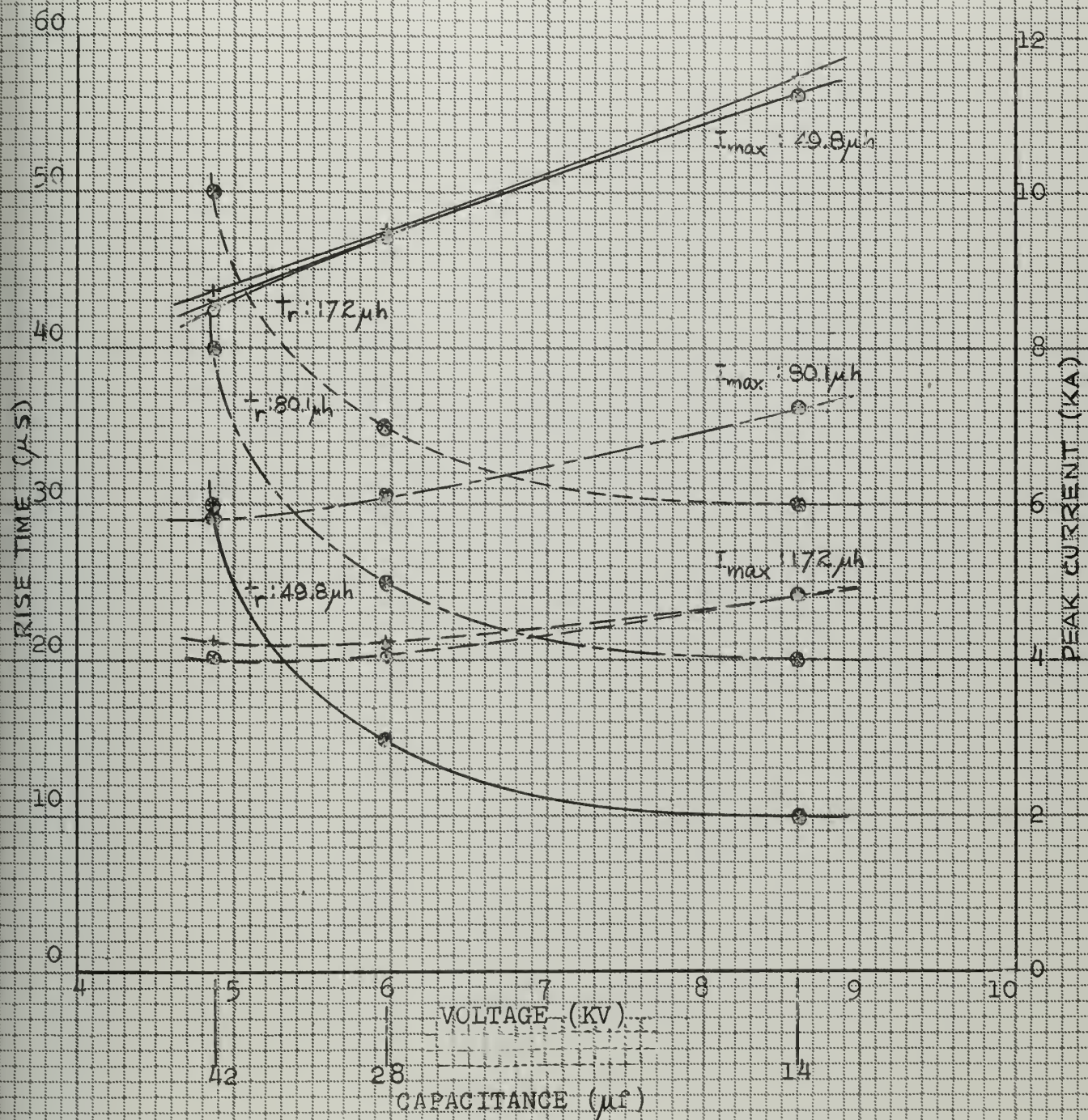
FIGURE VI

INFLUENCE OF L, C, AND PLATE THICKNESS ON
RING FREQUENCY AND DECAY TIME CONSTANT

500 JOULE INPUT

+ 1/4" Al Plate   x 1/8" Al Plate   o 1/16" Al Plate

35
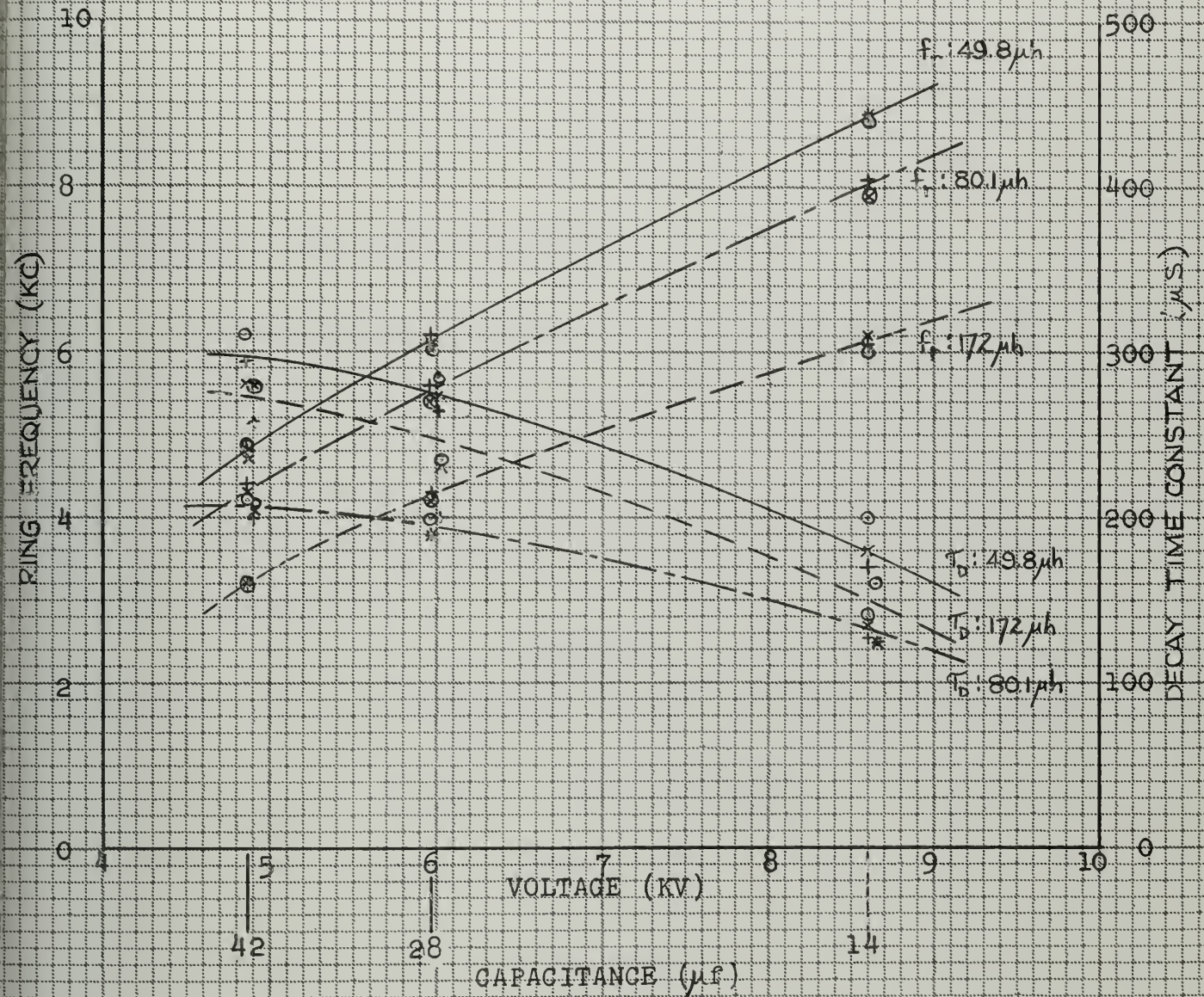
3. <u>Variation of V_o</u>: The changes in electrical rise time
and peak current which result from increasing energy input
by variation of capacitor bank voltage with other parameters
fixed (L = 49.8μh, C = 14μf) are shown in Figure VII.

4. <u>Variation of C</u>: The changes in electrical rise time
and peak current which result from increasing energy input
by variation of energy bank capacitance with other parameters
fixed (L = 49.8μh, V_o = 10 KV) are shown in Figure VIII.

B. <u>Pressure Pulse Characteristics</u>

1. <u>Comparison of liquids</u>: the characteristics of the
driven pulse* produced in each of the three liquids subjected
to comparative testing are summarized in Table II below. Tests
were conducted in an open, 10" cylinder, using the driver
illustrated in Figure II, and a Chesapeake Instrument Model
SB 154-D hydrophone.

<u>TABLE II</u>

PRESSURE PULSE CHARACTERISTICS OF WATER, PENTANE, AND GLYCERINE

Liquid	Rise Time (μs)	Peak Hydrophone Output (Volts)	Pulse Duration (μs)
water	75	450	170
pentane	75	352	168
glycerine	75	312	180

* The first positive pulse produced by the driver. In general, the
  subsequent history of the pressure signal proved to be a function
  of overall system characteristics, in that it depicted res-
  onances of the driven plate, the tank, and the hydrophone used in
  the test. As the system used did not closely resemble the con-
  templated ficility, it is feared that relatively little useful
  information can be extracted from the "tail" of the waveform.
  See DISCUSSION OF RESULTS.

FIGURE VII

INFLUENCE OF V_O ON RISE TIME AND PEAK CURRENT

L = 49.8 μh   C = 14 μf   1/4" Al Plate
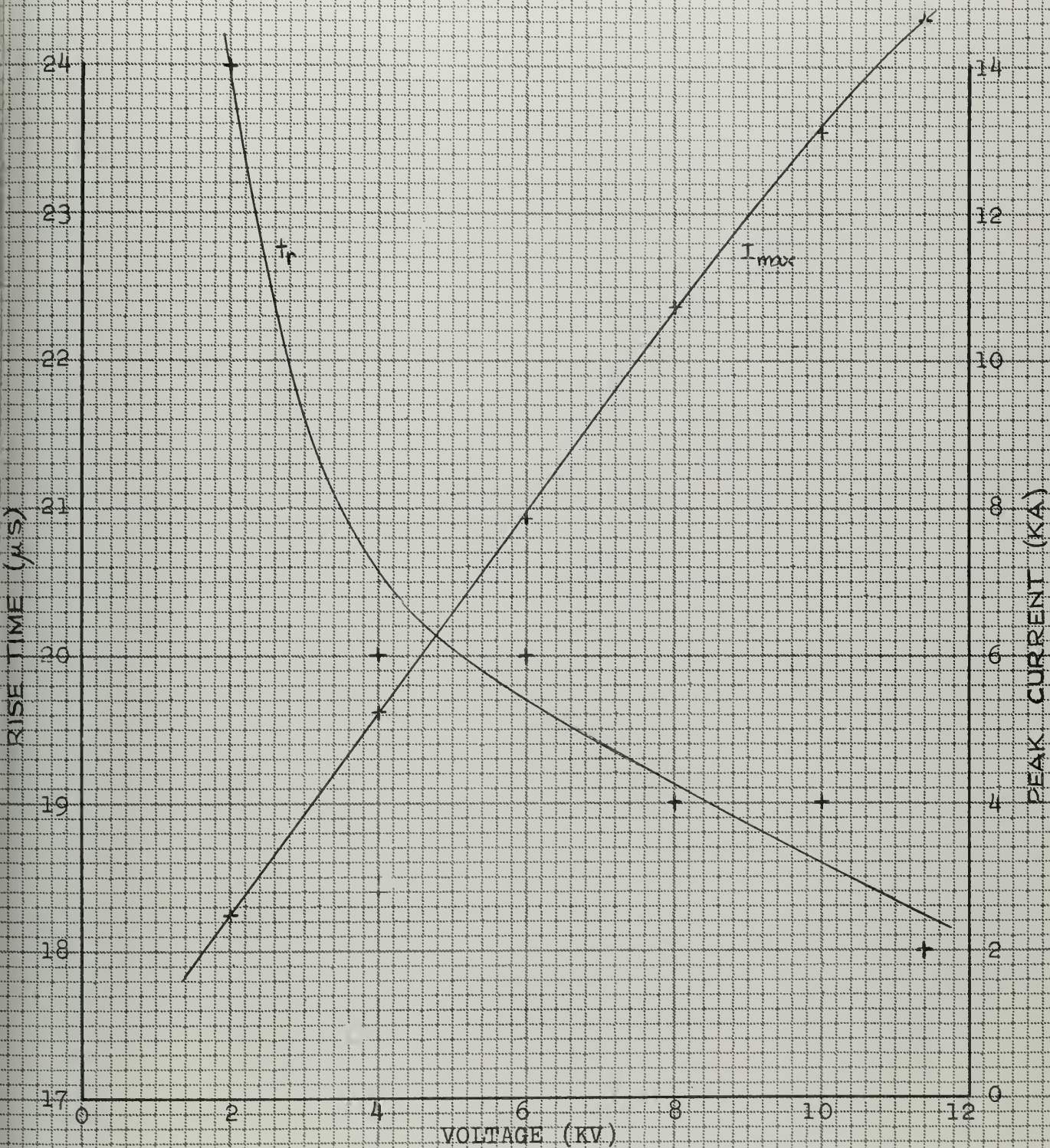
FIGURE VIII

INFLUENCE OF C ON RISE TIME AND PEAK CURRENT

L = 49.8 μh   V$_0$ = 10 KV   1/4" Al Plate
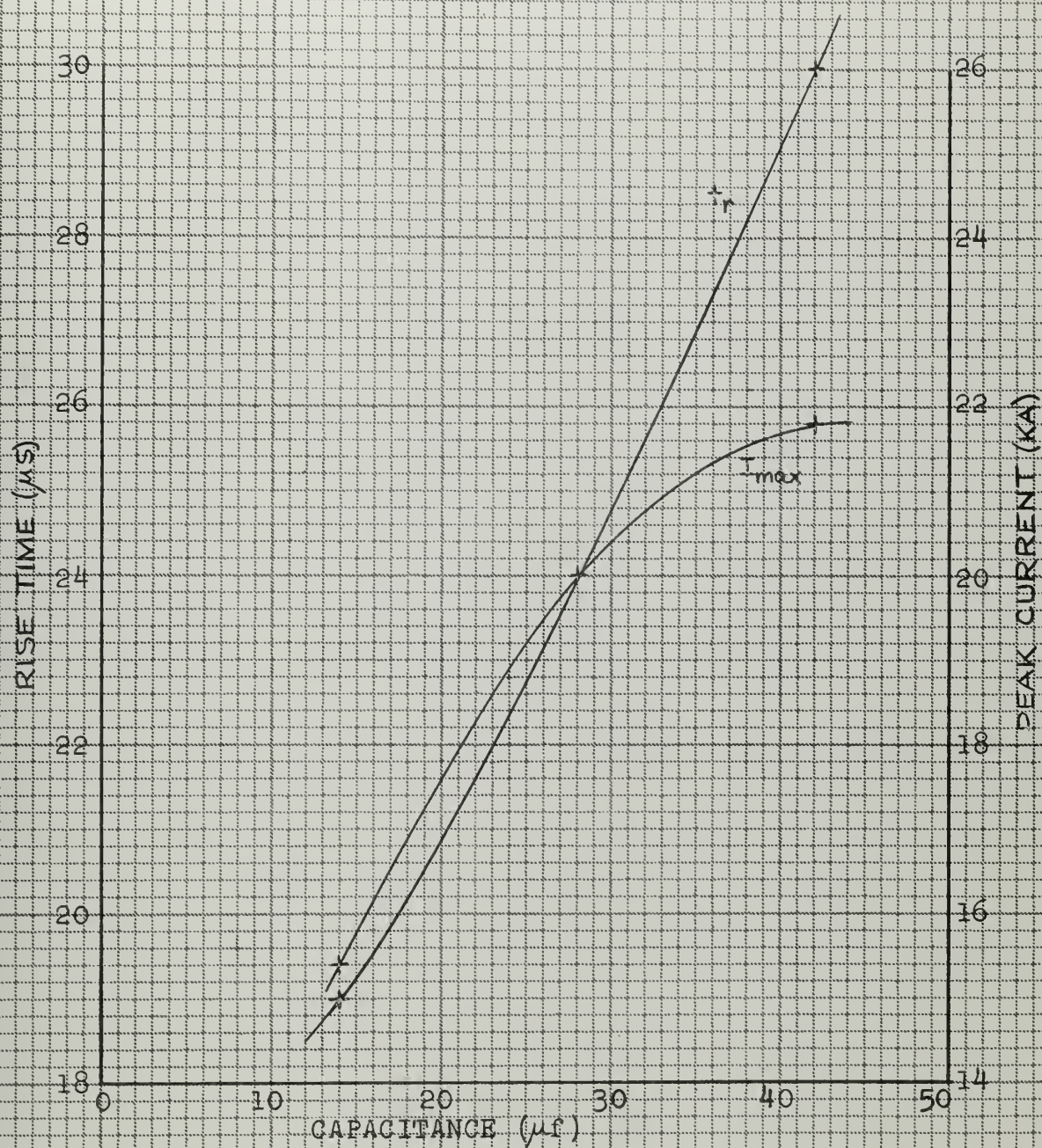
Inasmuch as neither pentane nor glycerine offered any significant advantage over water, the decision was made to use water as the test medium in all further tests.

2. Variation of L, C, and plate thickness at constant energy: In terms of the pressure pulse, vice electrical signature, the plot which corresponds to Figures V and VI is Figure IX, which depicts variation of peak hydrophone output and pulse duration (for a given variation in bank capacitance and plate thickness) for each coil tested. As mentioned in PROCEDURE, tests were conducted in a large, open tank: thus, test results--- particularly, peak amplitude--- are not directly comparable to results anticipated under more favorable conditions. (See Section 6 below.) Despite the above limitation, the data are of value in obtaining a relative assessment of driver performance following a given change in basic parameters. In short, the data can be used to establish trends, which in turn will be of use in system design.

To emphasize that facet of test data which is presumed to be of most value, and to facilitate correlation of test data recorded by various hydrophones, pressure pulse data have been plotted on a normalized basis, with a $49.8\,\mu h$, $14\,\mu f$, 500 watt second system with 1/4" Al driven plate taken as the reference standard for this series. The original, unnormalized data are tabulated, for reference purposes, in tables A-IV through A-VII of Appendex A.

It is interesting to note that in all tests in the range $14\,\mu f \leq C \leq 42\,\mu f$, observed rise time was pickup

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FIGURE IX

INFLUENCE OF L, C, AND PLATE THICKNESS ON
PULSE AMPLITUDE AND DURATION

500 JOULE INPUT

+ 1/4" Al Plate   x 1/8" Al Plate   o 1/16" Al Plate
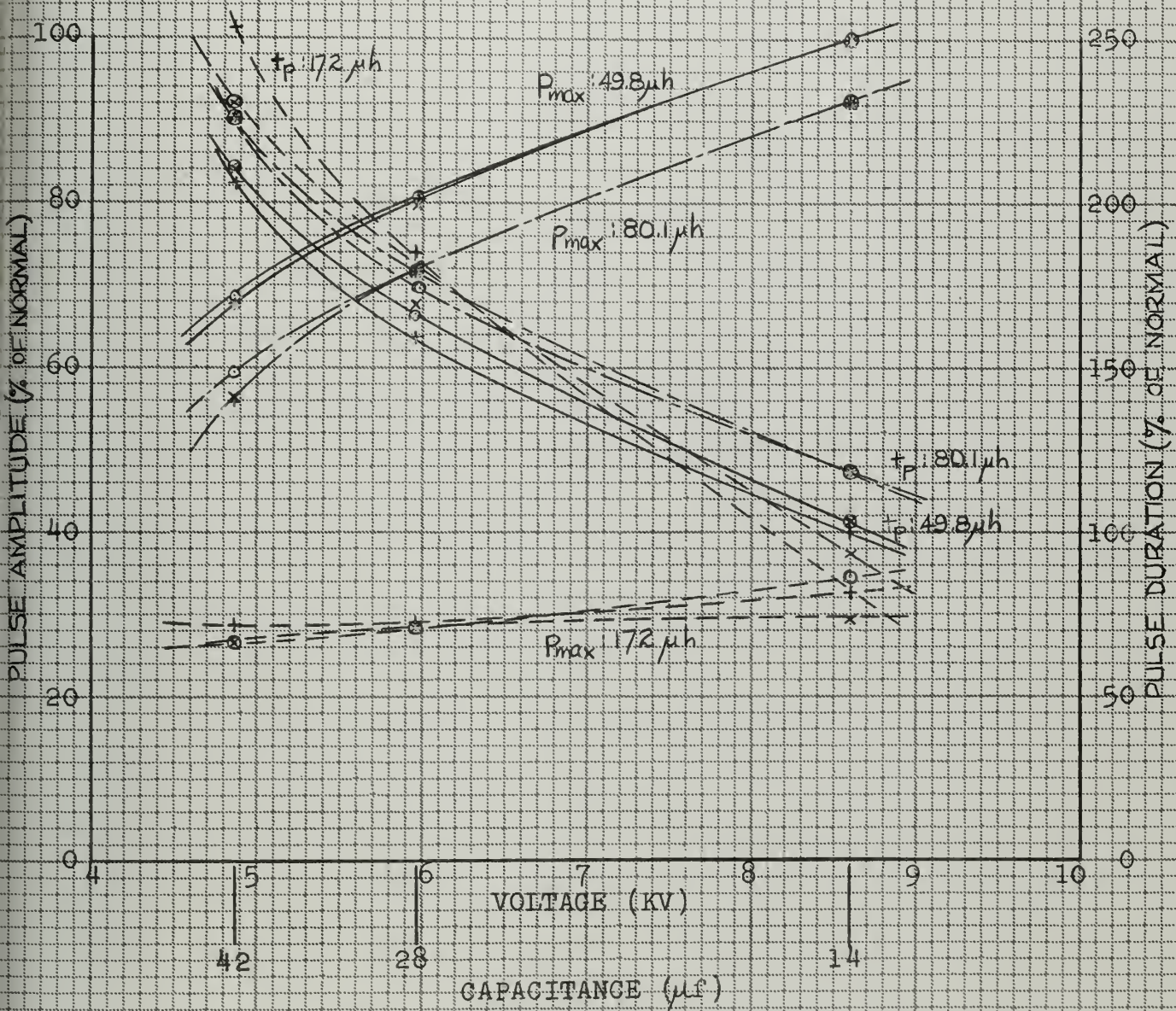
limited: that is, the rise time of the pressure pulse was apparently less than or equal to 1 μs, which was the minimum attainable rise time of the "fastest" hydrophone constructed. (This statement covers test series 2 through 5.) As can be seen in Table A-IV, some slowing of rise time was evident for C = 80 μf. The C = 80 μf points were omitted from Figure IX, however, as it was later learned that, due to an inaccurate voltmeter, these runs were conducted at an energy level of 695 watt seconds.

3. Variation of V_O: The changes in peak pressure and pulse duration which result from increasing energy input by variation of capacitor bank voltage with other parameters fixed (L = 49.8 μh, C = 14 μf) are shown in Figure X. The 8.6 KV level is used as a reference standard.

4. Variation of plate composition: Figure XI displays variation in peak pressure and pulse duration as a function of relative thickness of copper for a series of laminated plates of 1/16" nominal thickness. Tests were conducted at 10 KV, using the 49.8 μh coil and a 14 μf bank. All tests are related to a 1/4" Al plate standard.

5. Variation of C: The changes in peak pressure and pulse duration which result from increasing energy input by variation of energy bank capacitance with other parameters fixed (L = 49.8 μh, V_O = 10 KV) are shown in Figure XII. Reference standard is 1/4" Al plate with C = 14 μf.

6. Comparision of open tank and 10" cylinder: The characteristics of the driven pulse observed in each of the

FIGURE X

INFLUENCE OF V_O ON PULSE AMPLITUDE AND DURATION

$L = 49.8 \ \mu h$ $C = 14 \ \mu f$ 1/4" Al Plate
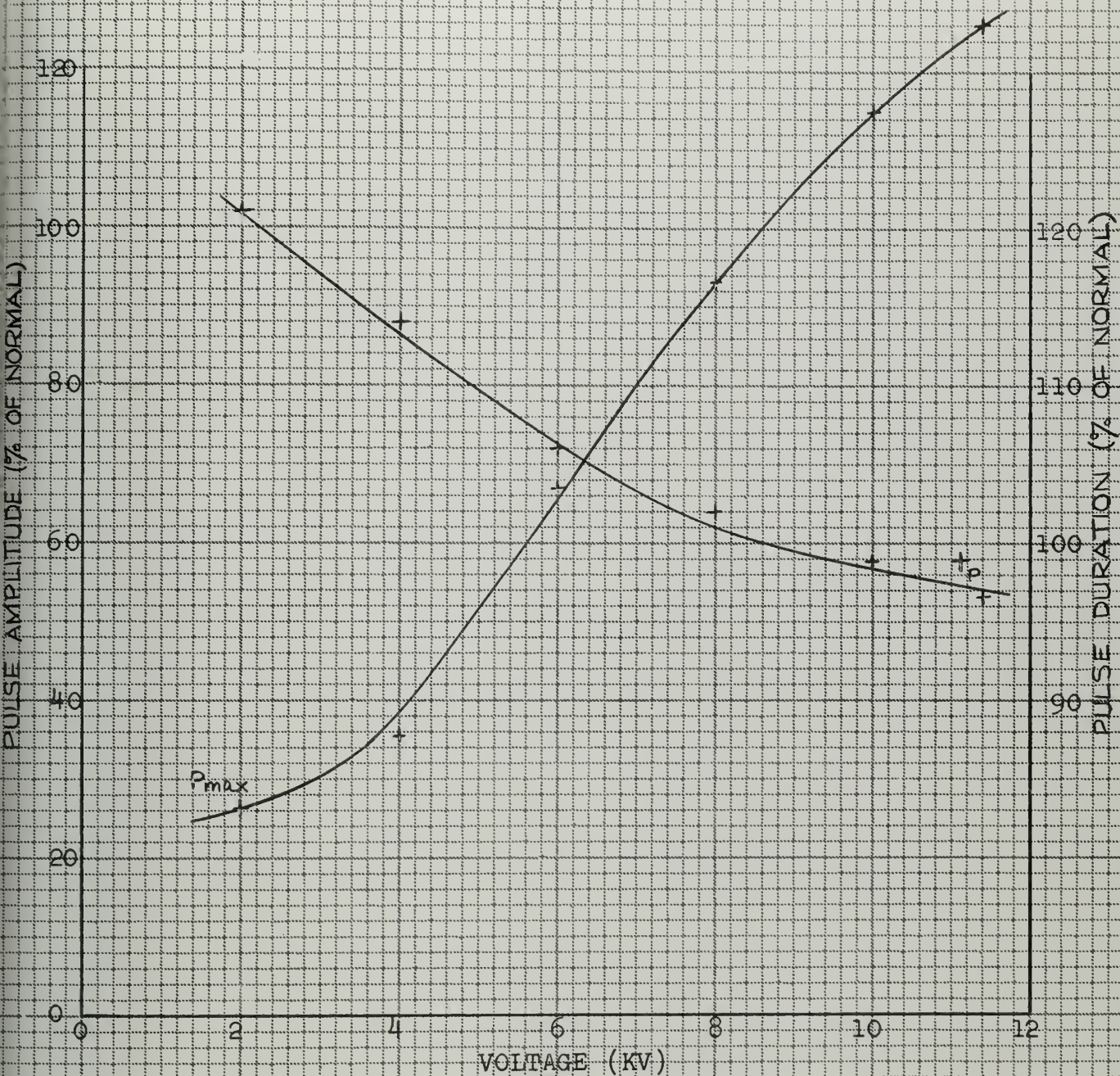
FIGURE XI

INFLUENCE OF PLATE COMPOSITION ON
PULSE AMPLITUDE AND DURATION

P_{max}: 49.8 μh

P_{max}: 80.1 μh

t_p: 49.1 μh

T_p: 80.1 μh

PULSE AMPLITUDE AND DURATION: PERCENT OF NORMAL

PERCENT OF TOTAL THICKNESS FORMED OF COPPER

PERCENT OF TOTAL THICKNESS FORMED OF ALUMINUM

$C = 14 \mu f$

$V_0 = 10$ KV

1/16" laminated plates

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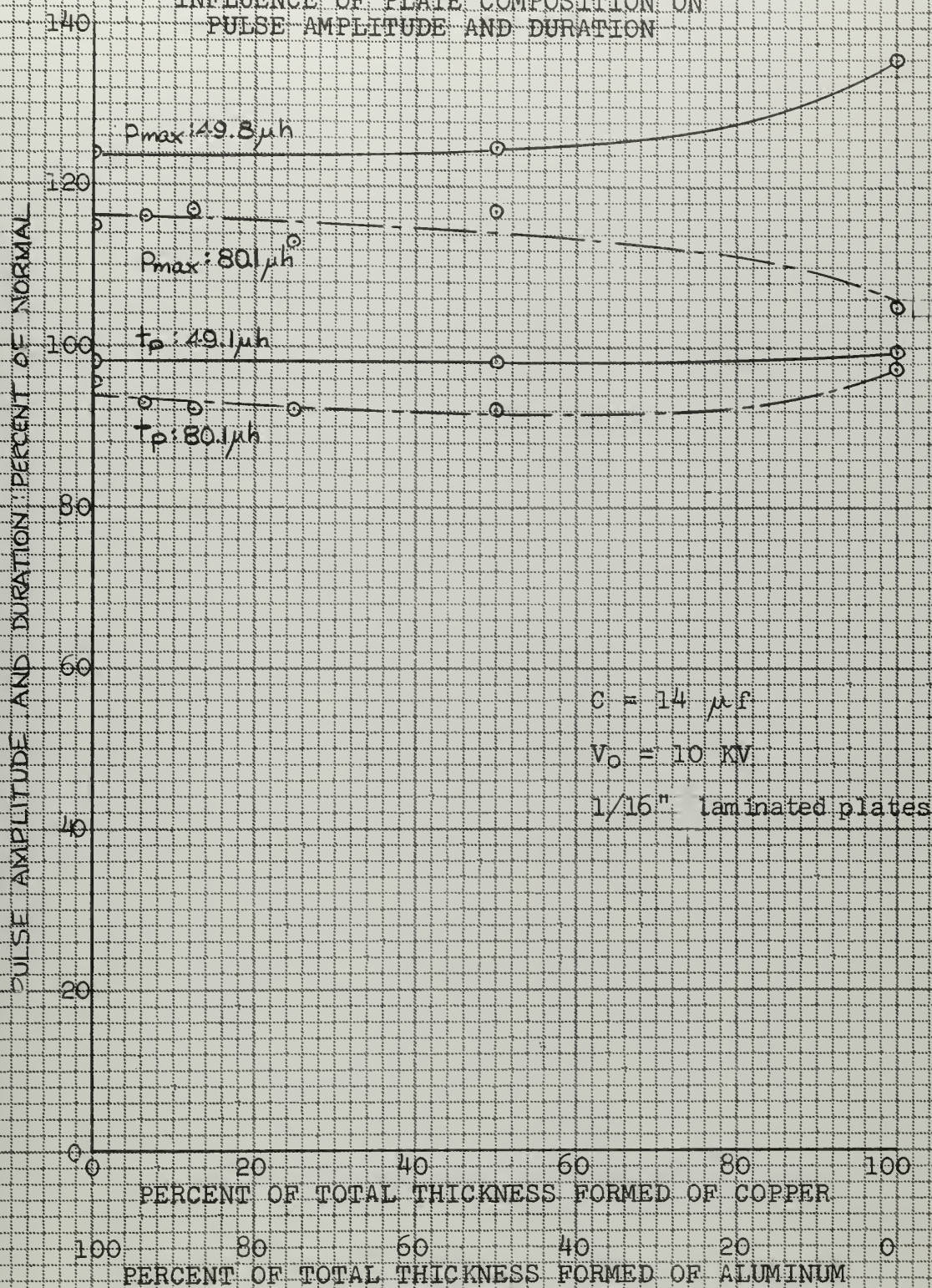
FIGURE XII

INFLUENCE OF C ON PULSE AMPLITUDE AND DURATION

$L = 49.8 \mu h$ $V_o = 10$ KV
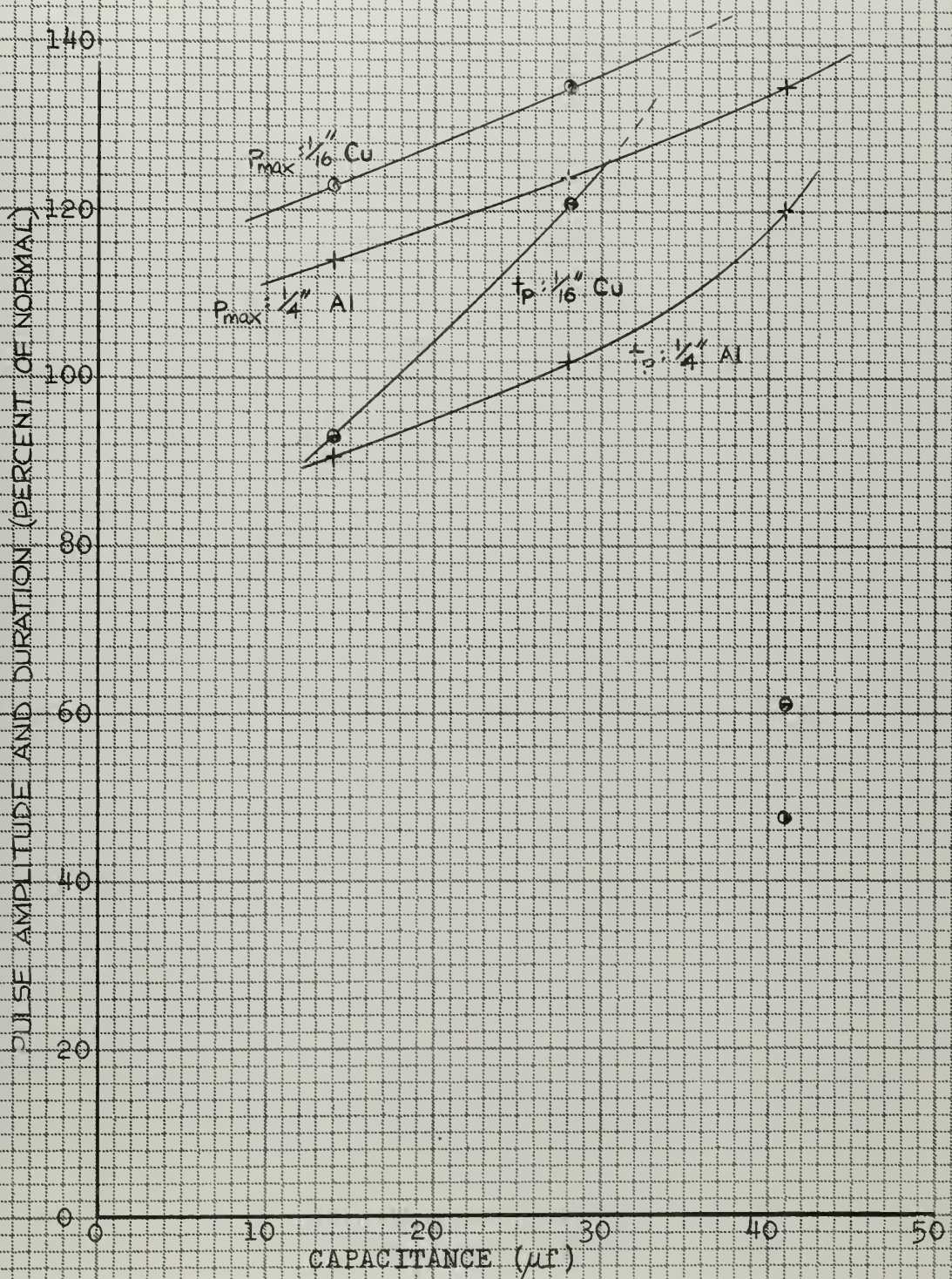
two test tanks cited are summarized in Table III below. This

comparison was made at 10 KV, with L = 49.8 μh, C = 14 μf:

TABLE III

COMPARISON OF TEST TANKS

Tank	Rise Time (μs)	Peak Hydrophone output (volts)	Pulse Duration (μs)
large, open tank	1	24.0	12
open 10" cylinder	6*	-520	28

* Vertical jump to -400 volts, followed by gradual rise to
  -520 volts.

IV. DISCUSSION OF RESULTS

A. Comparison of Liquids

As has been stated before (see Table II), neither pen-
tane nor glycerine offered any significant advantage over
water as a test medium, based on experiments conducted in
an open cylinder. Perhaps, in retrospect, this is not
astonishing: As stated, pentane was selected for testing
because the relatively rapid increase of acoustic velocity
with pressure indicated that liquid might effect significant
pulse steepening as the pressure pulse propagated through the
test chamber. However, the 5" spacing between the driver and
the pressure pickup would permit very little pulse steepening
unless the pressures generated on the face of the driving
plate were quite intense. Such was found not to be the case.

The selection of a 5" separation between the driver
and the pressure probe was based on the assumption of a 5"
spacing between the driver and the "target" end of the
hypothesized test facility. As mentioned, the existing mech-
anical facility uses repetitive internal reflection as a
means of generating prolonged pulses. Actually, there is
little choice in this matter: In general, it is not possible
to match acoustical impedances sufficiently well at the ends
of the chamber as to eliminate reflections, nor is it feasible
to construct a chamber sufficiently long that reflections can
be ignored. Thus, they must be utilized. However, the reflected
pulse repetition frequency of 3 KC achieved with the glycerine

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filled 20" chamber has proven to be a disadvantage: Cdr.
J.R. Baylis has mentioned that some components subjected
to testing were found to have mechanical resonances suf-
ficiently close to that frequency as to create problems.
Reducing the length of the chamber would raise the repetition
frequency, thus easing the problem of mechanical resonance,
and would also help compensate for the relatively shorter
duration pulses produced by the electrical driver, by spacing
them closer together in time. Considering the above, it
would appear reasonable to eliminate pentane from consider-
ation as a possible test medium.

On the other hand, despite its poor performance in the
experiment cited, glycerine may yet be worthy of consideration
as a test medium. As discussed in PROCEDURE, it is possible
that a liquid less compressible than water might result in
higher conversion efficiencies, provided that the liquid
were excluded from the region between the driving coil and plate,
and provided that the driver and the liquid completely filled
a constant volume system.

As it happens, the first provision mentioned above
must be met, in any event, in order to adapt the boomer for
service in an environment involving high hydrostatic pressures:
The output of early boomers was found to decrease rapidly
with increasing hydrostatic pressure. High-speed motion
pictures revealed that the driven plate separated from the
coil so rapidly that a vapor pocket formed behind the plate.
Thus, a pressure drop developed across the plate, equal to

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the difference between the hydrostatic pressure on the
face of the plate and the vapor pressure on the rear of the
plate. Because of this, increased hydrostatic pressure
(while vapor pressure remained essentially constant) resulted
in decreased output.

A solution to this problem has been devised by H.E.
Edgerton and S.O. Raymond (6,7). Basically, it consists of
encasing the driver assembly in a rubber boot, and utilizing
a regulated air supply to maintain air pressure in the boot
within a few psi of the hydrostatic pressure outside the boot.
A grooved plate is used to ensure a supply of air between the
plate and coil, and thus minimize pressure drop when the plate
is "fired". (Though the reduction in coupling caused by the
grooves has been found to result in about a 10% reduction in
output--- compared to a flat plate at one atmosphere--- the
output of the compensated array has actually been found to
increase with hydrostatic pressure up to about 2000 psi,
reaching a maximum about 25% higher than the flat plate at one
atmosphere.)

In any event, a driver so compensated--- immersed in a
pressure chamber--- fulfills both "provisions" discussed above.
It might well prove worthwhile to conduct a second comparative
test of water and glycerine, under such conditions.

B. Performance of Driver

In line with the above discussion of test media, it is
interesting to note that the degree of coupling between the

driving coil and plate is sufficiently "loose"--- as evi-
denced by the low conversion efficiencies measured for com-
mercial boomers--- as to completely divorce the electrical
behavior of the driver from the test medium. This is cer-
tainly verified by the identical electrical performance
observed when testing the driver illustrated in Figure II
in various liquids and in air, and is again reflected by the
very slight dependence on plate thickness--- i.e., driven
mass--- observed in Figures V and VI.

Figure V displays the effect of successively reducing
L and C in an attempt to reduce electrical rise time while
remaining at a given energy level. Above 6 KV, very little
was gained by further reduction of C, though rise time
remained sensitive to reduction of coil inductance. However,
it is apparent that peak currents increased rapidly as L was
reduced below 80 μh, thus increasing losses due to lead
resistance. Again, it is felt that it would not be feasible
to work with coils much smaller than 50 μh, if for no other
reason, because of the reduced service life resulting from
higher stresses of thermal and electrical origin, due to the
higher currents involved.

Figure IX depicts the variations in pressure pulse ampli-
tude and duration which correspond to the electrical phenomena
displayed in Figure V. As can be seen, use of the 49.8 μh
coil resulted in a slight increase in maximum pressure, com-
pared to the 80.1 μh coil, with a very slight reduction in
pulse duration. Accordingly, the 49.8 μh coil was selected

as the standard for further experimentation.

As was mention in RESULTS, it was found that any elec-
trical rise time less than 50 μs resulted in the generation
of a pulse with an essentially vertical leading edge. Com-
parision of Figures V and IX reveals an additional item of
interest in this situation: Reduction of electrical rise
time <u>below</u> the 50 μs level resulted in a gradual increase
in peak amplitude, but a <u>much more rapid decrease in pulse</u>
<u>duration</u>. Thus, it would appear unprofitable to reduce
electrical rise time any further than that level which just
suffices to produce the desired pressure signal.

It is also interesting to note that Figure IX again
indicated the relative unimportance of the mass of the driven
plate as a design parameter--- at least, within the ranges
considered. Though a very slight improvement in pressure
pulse characteristics resulted from the use of a thin plate
at low voltage levels (i.e., slower electrical rise time), this
improvement was hardly significant and, in general, disappeared
at higher voltages.

Figure XI represents the investigation of plate composition
as a parameter affecting driver output. It is recognized that
some variation of driven mass resulted from the use of lam-
inated plates of constant thickness; however, this variation
was of lesser magnitude than that investigated by the tests
depicted in Figure IX. Further, if Figure IX is to be believed,
these latter tests were conducted in a region in which the
variation of mass, per se, should not have affected output.

At best, the test results depicted in Figure XI were inconclusive. Certainly, there would appear to be no advantage in the use of laminated plates, as contrasted with solid plates of a single conductor. However, of the solid plates tested, the relative merits of Cu and Al were not clearly established by this test series. Accordingly, the decision was made to conduct further comparative testing.

Figures VII and VIII display the electrical performance of the driver as input energy level was systematically increased to the limits of the available facilities. In Figure VII, voltage was increased while capacitance was held fixed. As might be expected, peak currents increased nearly linearly with voltage, while rise time decreased. It is interesting to speculate about the deviation from linearity in the I-V relationship above 8 KV: Since the energy transferred to the liquid is electrically equivalent to a resistive loss, it is possible that this increase in apparent resistance might represent closer coupling to the driven plate. Perhaps the more rapid buildup of the magnetic field resulted in greater energy transfer before the plate could move away from the coil, thus decoupling the system. Figure X displays the related pressure pulse data, and it can be seen (as contrasted with the constant energy-increasing voltage case) that pulse duration fell much less rapidly than before, while peak pressure rose much more rapidly.

Figure VIII displays the effect of increasing supply bank capacitance to increase energy, while remaining at a con-

stant operating voltage. Electrical rise time is seen to increase rapidly, while peak currents rise, but at a decreasing rate. Inasmuch as electrical rise time remained well below the $50 \mu s$ level discussed previously, it would appear that considerably more capacitance could be tolerated in the circuit at 10 KV than at 4 KV--- or, in other words, it would be possible to design for an energy input in excess of the 2100 joules achieved here at 10 KV. It is also apparent, however, that an order of magnitude increase in energy level would require a voltage level higher than 10 KV.

Figure XII, in addition to being the companion piece to Figure VIII, again investigates the influence of plate conductivity on the output pulse. To minimize the effect of mass difference, a 1/4" Al plate and a 1/16" Cu plate were subjected to comparative testing. This time, the relative merits of Cu and Al would seem much more apparent: Use of the copper plate resulted in a reasonable improvement in both pulse amplitude and duration, and more significantly, the degree of improvement increased as more capacitance was added to the circuit to raise the energy input. On the other hand, the lower strength of the copper plate proved to be a fatal shortcoming: at an input level of 2100 joules, the copper plate failed structurally, resulting in permanent deformation and a sharply reduced output.

Now, granting that driver performance has been insensitive to mass within the range examined, it would obviously be possible to use a thicker copper plate to avoid failure at 2100 joules.

On the other hand, if we consider an eventual order of magnitude increase in energy level, it is certainly possible--- if not probable--- that eventually, the lower strength per unit mass realizable with copper would preclude the use of that metal in the driven plate.

As a final item in the analysis of test data, it is of interest to estimate the magnitude of the pressure pulse which might be produced by the boomer if driven, as contemplated, into an 8" closed cylinder.

Table III indicates that when driven into a thin-walled, 10" cylinder the magnitude of the hydrophone output was 520 volts. The hydrophone utilized for this test was the PZT-5 pickup illustrated in Figure IIIb. According to the manufacturer (8), nominal parameters for this crystal are:

$$g_{33} = 24.4 \times 10^{-3} \text{ volt-meter/newton}$$
$$K_{33} = 0.675$$
$$\epsilon\epsilon_o = 15.9 \times 10^{-9} \text{ farads/meter}$$
$$Y = 5.85 \times 10^{10} \text{ newtons/square meter}$$

Further, in metric units, cross-sectional area of the disk is 8.10×10^{-5} square meters, and its thickness is 1.522×10^{-3} meters. Using the method expounded by F.E. Perkins and P.S. Eagleson (9) to compute crystal sensitivity:

$$C_o = \epsilon\epsilon_o \frac{A}{t} = 84.6 \times 10^{-12} \text{ farads}$$

$$\alpha = \frac{g_{33}\epsilon\epsilon_o YA}{t} = 1.209 \times 10^{-1} \text{ coulombs/meter}$$

$$V_o/F = K_{33}^2/\alpha(1 + K_{33}^2) = 2.59 \text{ volts/newton}$$

$$V_o/p = 1.442 \text{ volts/ p.s.i.}$$

The crystal was placed in series with 63" of shielded conductor, rated at 24×10^{-12} farads/foot, and an oscilloscope with input capacitance equal to 20×10^{-12} farads. Allowing for the attenuation of a total series capacitance of approximately 150×10^{-12} farads:

$$V_s/p = V_o \left[Co/(Co + Cs) \right] = 0.521 \text{ volts/psi}$$

Thus, very crudely, an output level of 520 volts corresponds to a pressure signal of roughly 1000 psi.* Considering that this was the free-stream pressure--- analogous to the positive-going wave on a transmission line--- a test specimen mounted to a rigid end plate in a pressure chamber would see a pulse of roughly twice this magnitude, or 2000 psi. It might be noted that this pressure was developed with an energy input of 700 joules.

The fact must be stressed that the above estimate is quite crude: It would be valid for dynamic response within the "flat" portion of the crystal characteristics, but as is evidenced by the fact that rise time was observed to be pickup limited, appreciable pressure energy must have been distributed at frequencies above the crystal cutoff frequency. Actually, the only accurate method of determining pressure level would be to calibrate the crystal used by subjecting

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* Albers (10) reports that W. Eisenmenger has achieved 700-atmosphere shock wave by using a similar driver to implode a piece of copper foil into a water-filled tube.

FIGURE XIII

SUGGESTED DRIVER DESIGN
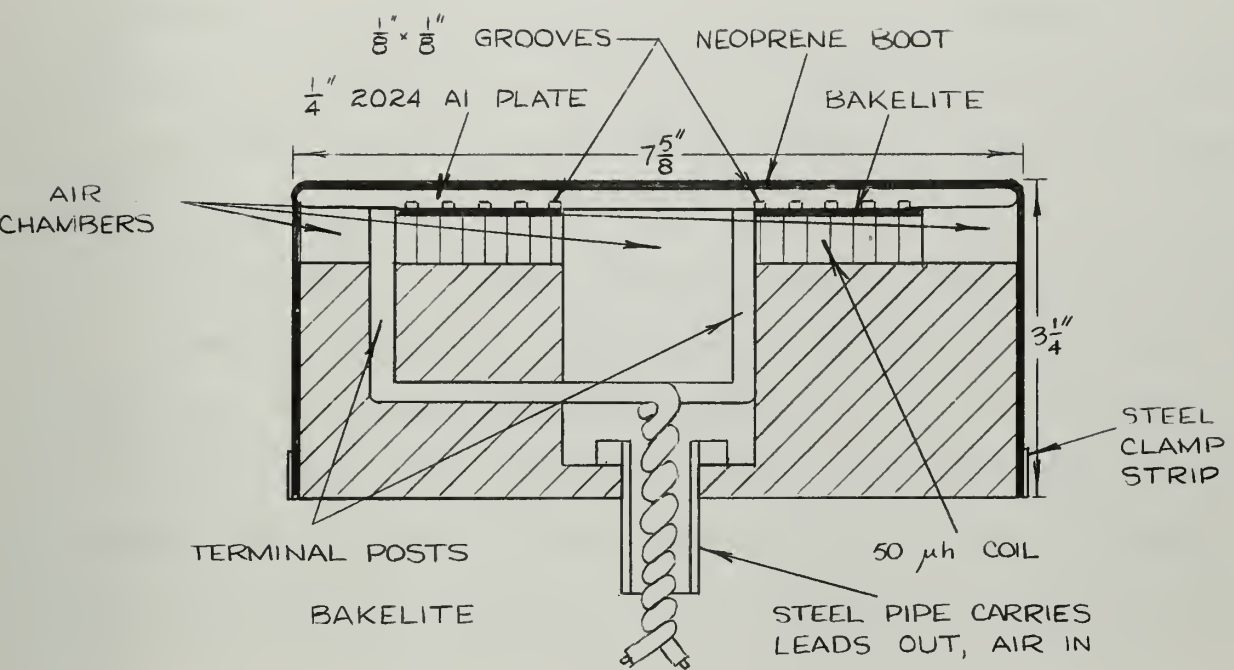
affect driver performance, it would be well to minimize
the degree of coupling between the coil and the pressure
chamber. The less the inductance of the coil used, the
smaller its outer diameter--- thus, less coupling with the
chamber should occur at the lower limit of the range of
inductance discussed.

Though a 1/4" 2024 Al alloy plate has been specified,
it may prove necessary to shift to a 7075 alloy and/or
a thicker plate, at higher energies. In this respect, it
would also be interesting to further investigate the possible
use of copper to capitalize upon the improved output character-
istics discussed above.

Figure XIV is a rough schematic of the proposed facility.

Pending successful completion of the additional tests
indicated, it would tentatively appear feasible to develope
an electrically driven hydraulic shock generator, with input
energy of up to 25,000 joules, operating at 25 KV. It might
prove feasible to develope an even more powerful test facility.

FIGURE XIV

SCHEMATIC OF PROPOSED TEST FACILITY
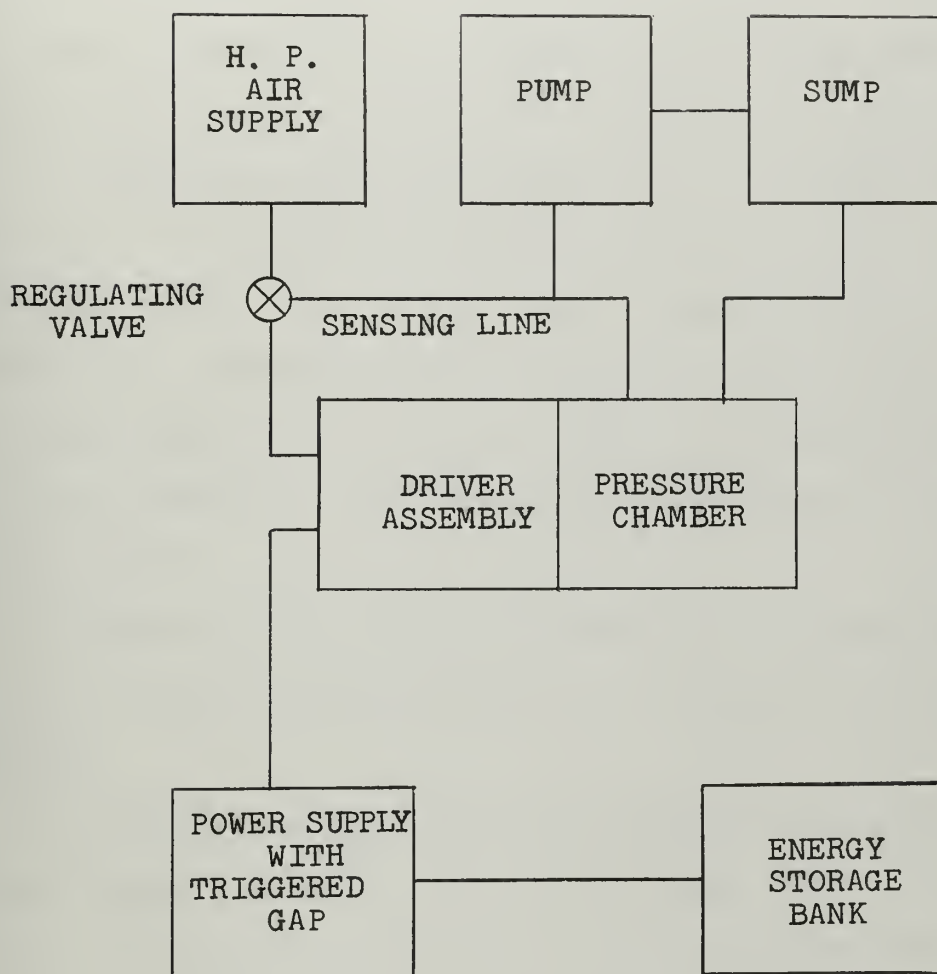
V. CONCLUSIONS

1. The boomer has been found to hold real promise
as a driver for an underwater explosion simulator.

2. Modification of the basic boomer design to provide
for an electrical rise time of about 5C μs, in conjunction
with other modifications discussed in the text, appears to be
the optimum design for generation of hydraulic shock.

3. <u>Given the above conditions</u>, it is estimated that
the boomer will produce a pressure pulse, as seen by the test
specimen, with a rise time of 1 μs or less, a peak pressure
of 2000 psi or higher, and a duration of about 35 μs, for
an energy input of 700 joules. Increases in peak pressure
and pulse duration can be achieved by operation at higher
energy levels.

4. Pending the successful conclusion of additional
testing, energy inputs in excess of 25,000 joules would seem
feasible.

5. Either water or glycerine appear to hold promise as
a test medium for use in conjunction with this type of
driver: In any event, the relatively loose coupling of the
driver to the liquid permit substitution of different test
media with no effect on electrical performance of the driver.

6. The pressure chamber used in conjunction with the
above driver should be of a length not to exceed 8": However,
should it become necessary to test specimens which penetrated
more than 4" into the chamber, additional flanged sections could

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be used to extend the length of the chamber for such tests.

VI. RECOMMENDATIONS

A. It is recommended that the proposed driver design be subjected to extended testing, as follows:

    1. Additional testing at current energy levels, but within the proposed pressure chamber, to verify system performance at various hydrostatic pressures.

    2. Additional comparative testing of water and glycerine as test media.

    3. Further investigation of input-output energy relations by extension of energy bank capacitance, in steps, to a level of approximately twice the range covered herein, and by extension of operating voltage, in steps, to a level of about 25 KV.

    4. Further investigation of the feasibility of using a copper driven plate at high energy levels.

B. Contingent upon the successful conclusion of the above test program, it is recommended that serious thought be given to the establishment of an electrically driven hydraulic shock test facility.

APPENDIX

APPENDIX A

TABLE A-I

INFLUENCE OF COIL INDUCTANCE, BANK CAPACITANCE, AND PLATE THICKNESS
ON ELECTRICAL SIGNATURE OF DRIVER WITH 500 JOULE INPUT

$L(\mu h)$	$C(\mu f)$	$V_O(KV)$	Plate	Rise Time (μs)	I_{max} (KA)	Ring Frequency (KC)	Decay Time Constant (μs)
49.8	80	3.6	1/4" Al	45	2.91	3.2	280
			1/8" Al	45	2.88	3.1	280
			1/16" Al	45	2.88	3.1	285
	42	4.87	1/4" Al	30	8.77	4.8	295
			1/8" Al	30	8.59	4.7	280
			1/16" Al	30	8.47	4.9	310
	28	5.97	1/4" Al	15	9.53	6.2	265
			1/8" Al	15	9.41	6.1	275
			1/16" Al	15	9.41	6.0	285
	14	8.60	1/4" Al	10	11.52	8.9	170
			1/8" Al	10	11.28	8.9	180
			1/16" Al	10	11.28	8.8	200
80.1	80	3.6	1/4" Al	50	2.48	2.8	280
			1/8" Al	50	2.33	2.8	300
			1/16" Al	50	2.40	2.9	290
	42	4.87	1/4" Al	40	5.86	4.4	200
			1/8" Al	40	5.86	4.3	210
			1/16" Al	40	5.86	4.2	220
	28	5.97	1/4" Al	25	6.14	5.6	190
			1/8" Al	25	6.14	5.4	190
			1/16" Al	25	6.14	5.4	200

L(μh)	C(μf)	V_o(KV)	Plate	Rise Time (μs)	I_{max} (KA)	Ring Frequency (KC)	Decay Time Constant (μs)
	14	8.60	1/4" Al	20	7.23	8.1	128
			1/8" Al	20	7.23	7.9	135
			1/16"Al	20	7.23	7.9	142
172	80	3.6	1/4" Al	60	1.74	2.0	300
			1/8" Al	60	1.60	2.1	340
			1/16" Al	55	1.60	2.1	330
	42	4.87	1/4" Al	50	4.25	3.2	258
			1/8" Al	50	4.04	3.2	280
			1/16" Al	50	4.04	3.2	280
	28	5.97	1/4" Al	35	4.25	4.3	200
			1/8" Al	35	4.14	4.2	230
			1/16"Al	35	4.04	4.2	235
	14	8.60	1/4" Al	30	4.86	6.1	125
			1/8" Al	30	4.86	6.2	125
			1/16"Al	30	4.86	6.0	160

TABLE A-II

INFLUENCE OF INITIAL VOLTAGE ON ELECTRICAL SIGNATURE
OF DRIVER WITH OTHER PARAMETERS FIXED

$L(\mu h)$	$C(\mu f)$	Plate	$V_O(KV)$	Rise Time (μs)	I_{max} (KA)	Ring Frequency (KC)	Decay Time Constant (μs)
49.8	14	1/4" Al	2	24	2.47	11.2	190
			4	20	5.24	9.3	175
			6	20	7.86	9.3	160
			8	19	10.77	9.1	144
			10	19	13.10	9.1	160
			11.4	18	14.62	8.9	160

TABLE A-III

INFLUENCE OF CAPACITANCE ON ELECTRICAL SIGNATURE
OF DRIVER WITH OTHER PARAMETERS FIXED

$L(\mu h)$	Plate	$V_O(KV)$	$C(\mu f)$	Rise Time (μs)	I_{max} (KA)	Ring Frequency (KC)	Decay Time Constant (μs)
49.8	1/4" Al	10	14	19	15.4	9.1	165
			28	24	20.0	6.2	200
			42	30	21.8	4.5	204

TABLE A-IV

INFLUENCE OF COIL INDUCTANCE, BANK CAPACITANCE, AND PLATE THICKNESS ON PRESSURE PULSE WITH 500 JOULE INPUT

Measurements taken with a 0.710" x 0.044" quartz disk pickup

$L(\mu h)$	$C(\mu f)$	$V_O(KV)$	Plate	Rise Time (μs)	Peak Hydrophone Output (Volts)	Pulse Duration (μs)
49.8	80	3.6	1/4" Al	8*	46.6	71.4
			1/8" Al	8	50.0	71.4
			1/16" Al	8	56.0	71.4
	42	4.87	1/4" Al	6*	57.0	50.5
			1/8" Al	6	57.0	51.5
			1/16" Al	6	57.7	52.0
	28	5.97	1/4" Al	6*	67.5	39.0
			1/8" Al	6	67.0	41.5
			1/16" Al	6	67.8	40.0
	14	8.60	1/4" Al	6*	84.0	24.5
			1/8" Al	6	84.0	26.2
			1/16" Al	6	84.0	26.4
80.1	80	3.6	1/4" Al	8*	37.7	77.5
			1/8" Al	8	39.6	77.5
			1/16" Al	8	44.3	77.5
	42	4.87	1/4" Al	6*	47.0	55.5
			1/8" Al	6	47.5	55.5
			1/16" Al	6	50.0	55.5

* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.

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L(μh)	C(μf)	V_O(KV)	Plate	Rise Time (μs)	Peak Hydrophone Output (Volts)	Pulse Duration (μs)
	28	5.97	1/4" Al	6*	58.5	44.6
			1/8" Al	6	58.5	44.6
			1/16" Al	6	58.5	43.4
	14	8.60	1/4" Al	6*	77.5	29.2
			1/8" Al	6	77.5	29.0
			1/16" Al	6	77.5	29.0
172	80	3.6	1/4" Al	8*	22.8	85.0
			1/8" Al	8	23.9	85.0
			1/16" Al	8	24.3	85.0
	42	4.87	1/4" Al	6*	24.0	62.0
			1/8" Al	6	22.4	56.1
			1/16" Al	6	22.4	56.0
	28	5.97	1/4" Al	6*	24.4	45.4
			1/8" Al	6	24.0	44.0
			1/16" Al	6	24.0	43.0
	14	8.60	1/4" Al	6*	27.2	20.6
			1/8" Al	6	24.6	22.8
			1/16" Al	6	29.2	24.6

* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.

TABLE A-V

INFLUENCE OF INITIAL VOLTAGE ON PRESSURE PULSE
WITH OTHER PARAMETERS FIXED

Measurements taken with a 0.400" x 0.060" PZT-5 disk pickup

$L(\mu h)$	$C(\mu f)$	Plate	$V_O(KV)$	Rise Time (μs)	Peak Hydrophone Output (Volts)	Pulse Duration (μs)
49.8	14	1/4" Al	2	1*	5.0	16.0
			4	1	7.0	15.1
			6	1	12.8	14.0
			8	1	18.0	13.5
			10	1	22.0	13.1
			11.4	1	24.0	12.8

TABLE A-VI

INFLUENCE OF PLATE COMPOSITION ON PRESSURE PULSE
WITH OTHER PARAMETERS FIXED

For a series of Cu-Al laminated plates of 1/16" nominal thickness

$L(\mu h)$	$C(\mu f)$	$V_O(KV)$	% Cu	Rise Time (μs)	Peak Hydrophone Output (Volts)	Pulse Duration (μs)
80.1	14	10	0	50*	890 (1)	145
			6.5	50	900	141
			12.5	50	905	140
			25	50	875	140
			50	50	910	140
			100	50	814	148

(1) Measurements taken with Chesapeake Instrument Model SB 154-D hydrophone

* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.

TABLE A-VI (cont'd)

L(μh)	C(μf)	V$_0$(KV)	% Cu	Rise Time (μs)	Peak Hydrophone Output (Volts)	Pulse Duration (μs)
49.8	14	10	0	1*	24.0 (2)	13.0
			50	1	24.2	13.0
			100	1	26.2	13.2

(2) Measurements taken with 0.400" x 0.060" PZT-5 wafer

TABLE A-VII

INFLUENCE OF CAPACITANCE ON PRESSURE PULSE WITH OTHER PARAMETERS FIXED

Measurements taken with 0.400" x 0.060" PZT-5 wafer

L(μh)	V$_0$(KV)	Plate	C(μf)	Rise Time (μs)	Peak Hydrophone Output (Volts)	Pulse Duration (μs)
49.8	10	1/16" Cu	14	1*	23.8	12.3
			28	1	26.0	16.0
			42	1	9.2	8.1
		1/4" Al	14	1*	22.0	12.0
			28	1	24.0	13.5
			42	1	26.0	15.9

* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.
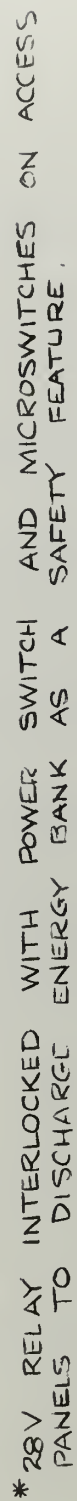
APPENDIX C

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